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Design of a Smart Ventilation System for 25 tons Cucumber Fruits Capacity Cold Room

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Abstract

An automated cold storage system for fresh cucumber fruits was designed in this study. The goal of the research was to create an effective smart cold storage facility for 25 tons of cucumber fruits. Results obtained from the design calculations depicted that the total volume occupied by the fruits was 21.25 m^3, the total internal surface area of the cold room was 252 m3, and the total heat transfer of the system was 126694.56 kcal/24h. The respiration heat load was 19,000 kcal/24h and the refrigeration capacity was 34240.46 kcal/h. Remarkably, the cool room will require 6 units of air conditioning machine each having capacity of 2 tons (7.04 kW) of refrigeration. The design used sensor, a microcontroller (Arduino Uno), relay module and control device, to monitor the environmental conditions inside the cold room. This designed structure considering the prevailing climatic conditions of southern Nigeria, is a commendable effort as it will help to address the specific cold storage needs of the region.

Keywords: Arduino UNO, factor of safety, food security, refrigeration capacity, temperature sensor

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1.0 Introduction

Cucumber (*Cucumis sativus* L.) belonging to the *Cucurbitaceae* family is widely cultivated crop due to its high nutritional and pharmaceutical attributes. Cucumber fruit is produced through inferior ovary, and the fruit comes in various colors, shapes and sizes. The global cucumber production is approximately 93.6 million tons from about 2.2 million hectares of cultivated land, according to the information provided by the Food and Agriculture Organization (FAO) in 2022 (FAOSTAT, 2023). The fruits contain numerous phytonutrients and anti-inflammatory compounds, which have the potential normalizing the blood sugars level, promote skin health, prevent heart diseases, encourage hydration and hinder the formation of cancers cells (Pal *et al.*, 2020; Khalid *et al*., 2022).Being agricultural products, the bioengineering properties of the fruit are influenced by the variety, soil chemical composition, maturity stage, farming method adopted, post-harvest operations and the prevailing environmental conditions (Ahmed *et al*., 2022; Grumet *et al*., 2022; Rajeev *et al.*, 2022; Beautin Nirsha *et al*., 2023).

The implementation of modern technology solutions to food management contributes to the efficient supply chain of food products (Umamaheswari *et a*l., 2020).Adequate food preservation techniques areessential criteria in attaining food security. Poor storage conditions are a significant contributing factor to food losses in the agricultural produce value chain (Onyeaka *et al*., 2021; Xylia *et al*., 2022). As a perishable biomaterial, cucumber fruitquality declines progressively during storage, and more rapidly under unfavorable storage conditions - high temperature and low relative humidity (Eboibi *et al*., 2018; Owoyem *et al*., 2021; Jahan *et al*., 2022). Cold storage method is the major and effective preservation method for several agricultural products. It helps to retain the freshness, quantity and nutritional quality of the produce during storage. This storage operation helps to retain the quality and quantity attributes of the stored items (Bai *et al*., 2023). Respiration rate and microbial activities are suppressed during cool storage operation; hence, the rate of deterioration of the stored product can be reduced to an appreciable level, resulting in increment in the shelf life of the product (Imaizumi *et al*., 2018).

Several designs using airflow facilities (including heat exchangers), to maintain uniform internal temperatures inside the storage structures have been carried out. The goal of those designs was to create a conducive environment for the stored item, where the temperature, humidity, and airflow are effectively monitored to preserve the quality and freshness of perishable produce (Duret *et al*., 2014; Getahun *et al*., 2017; Nasser Eddine *et al.*, 2022; Idama and Ekruyota, 2023). Despite the advantageous nature of cool storage system, cucumber fruit is highly susceptible to chilling injury at a temperature lower than 10°C during storage. Literature reviewed that there is design cool storage structure for cucumber fruits in southern Nigeria, considering the prevailing climatic conditions of the region. There the purpose of this work is to design a smart cool storage structure that can accommodate 25,000 kg of fresh cucumber fruits.

2.0 Design Methodology

The cool room will have internal dimensions of Length (22 m), Breadth (9.5 m) and Height (4.0 m). Figures 1 shows the plan of the cool room.

2.1 Design for the cooling structure

Some parameters required for designing the 25-ton cold room for storing cucumber fruits include the following: Ideal storage temperature(10°C), ideal relative humidity(RH) 90%,

external "outdoor" environmental conditions (30°C and 75% RH), Heat of respiration (760 Kcal/ton/24h) and specific heat (20% M.C) is 0.289 Kcal/Kg°C (Fasina and Fleming, 2001).

Basic physical characteristics of cucumber fruit Mass = 1 kg, Length = 0.3, width = 0.1 m, volume = 0.00085 m^3, and Bulk density = 1176 kg/m^3. These values were obtained after repeated measurement of 100 units of cucumber fruits.

2.1.2 Design of the cold room capacity

Total number of cucumber fruits to be stored in the cool room can be calculated through Equation 1.

$$number\ fruits = \frac{total\ capacity\ of\ the\ ware\ house}{mass\ of\ one\ cucumber} \quad (1)$$

$$= \frac{25{,}000}{1}$$

= 25,000 cucumber fruits

The total volume occupied by these 25,000 fruits is calculated by using Equation 2.

$$\sum Volume = volume\ per\ fruit \times number\ of\ fruits \quad (2)$$

Σ volume = 0.00085 m^3 x 25,000**= 21.25 m^3**

Internal dimensions

Length = 22 m
Breadth = 9.5 m
Height = 4.0 m
Total internal volume = 22 m x 9.5 m x 4.0 m.
= 836 m^3

2.1.3 Design of containers used for the fruits storage

The cucumber will be packaged (stored) in paper carton boxes, which will be placed in wooden shelves inside the cold room. Each carton box has the following dimensions = length (0.6 m)by width (0.5 m) by height (0.4 m).
Therefore each box = 0.6 m x 0.5 m x 0.4 m = **0.12 m^3**.

Referring to the mechanical properties of cucumber fruits as outlined by Eboibi and Uguru (2017), it is established that each carton can adequately accommodate 40 cucumber fruits. Consequently, the total number of cartons needed to package the 25,000 fruits can be determined using Equation 3.

$$\text{Number of cartons} = \frac{total\ number\ of\ cucumber\ fruits}{number\ per\ carton} \quad (3)$$

$$= \frac{25000}{40}$$

= 625 paper cartons

Consequently, the total volume occupied by the 625 carton boxes = 0.12 x 625

= 75 m^3

Engineering properties of the paper carton

Mass of each paper carton = 2 kg
Specific heat of paper carton = 0.33 Kcal/Kg°C (Engineering ToolBox, 2003)
Net mass of each carton box = mass of each carton box + mass of the content (40 fruits)

= 2 kg + 40 kg **= 42 kg**

2.1.4 External dimensions of the cool room

The wall of the cold room will be constructed with the following materials: Six inches (0.152 m) sandcrete blocks, concrete floor with 0.152 m thickness, rendering (cement mortar) of 0.05 m thickness 0.05 m, and insolating ceiling material with thickness of 0.01 m.

Therefore:
Length = 22 m + 0.304 m (two walls at 0.152 m each) + 0.1 m (2 faces rendering) = **22.404 m**
Breadth = 9.5 m + 0.304 m (walls) + 0.1 m (2 faces rendering) = **9.904 m**
Height = 4 m (to the roofing level) + 0.152 m of floor thickness + 0.152 m concrete decking + 0.01m ceiling + 0.05 m (1 face rendering) = **4.364 m**

Total external volume = 22.304 x 9.804 x 4.152
= 968.325 m^3

Total volume of materials used for the building walls and floor construction is calculated through Equation 4.

$T_M = \sum E_m - \sum E_i$ 4

Where ΣE_m = total external volume, ΣE_i = total internal volume, T_M = total materials used
Total volume of materials used = 968.325 m^3 – 836 m^3
= 132.325 m^3.

2.1.5 Arrangement of the cartons inside the cold room

The cartons will be placed in shelves inside the cold room as shown in Figure 1 for easy accessibility and ventilation of the cold room.

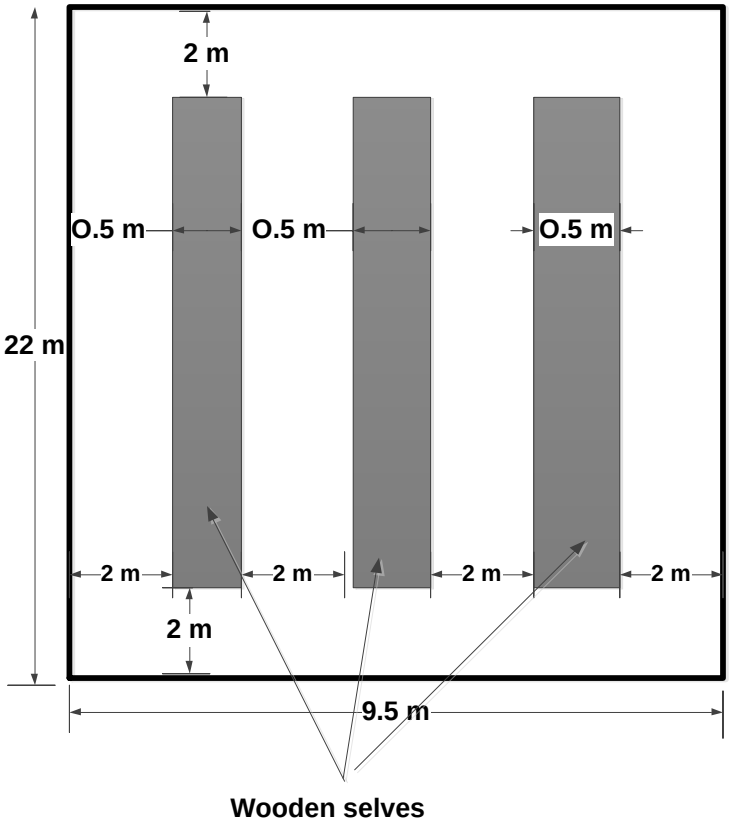


Figure 1: Arrangement of the wooden shelves

Free space (volume) inside the cold room

Total free space inside the cold room = total internal volume – (total volume cucumber fruits cartons+ total volume of the wooden shelves).

Volume of the wooden shelves used in storing the cucumber fruits = **1.011 m^3**.
Therefore free volume = 836 m^3 – (75 m^3 + 1.011m^3)
= **759.989 m^3**.

2.2 Calculating Cooling Loads

2.2.1 Heat transfer through the wall materials

Some essential parameters required to calculate the heat transfer through the walls:

i. Thermal conductivity of the sandcrete brick = 0.7 kcal/m/h^{o}C
ii. A thermal conductivity of cement mortar = 1.122 kcal/m/h^{o}C (Bamogo *et al*., 2023).
iii. R-values used here are R1.5, R2.5 and R2.5 for the walls, ceilings, and floors respectively as stated by Aldawi and Alam (2016). From relevant documents the outside (ambient) temperature (To) of the region is 30^{o}C, and ideal storage temperature of cucumber fruit is 10^{o}C.

Total internal surface area of the cold room is calculated through Equation 5.
Total surface area = effective length + effective breadth 5
Effective length = (2 x 22) x height of the building
= 44 x 4
= 176 m^2
Effective breath = (2 x 9.5) x height of the building
= 19 m x 4
= 76 m^2

Therefore internal total surface area of the cold room = 88 m^2x 76 m^2
= 252 m^3

Equation 6 was used to calculate the overall heat transfer coefficient of the wall component of the cool room.

$$U = \frac{T_1}{TC_1} + \frac{T_2}{TC_2} \quad (6)$$

Where:
T_1 is the thickness of the wall, T_{C1} is the thermal conductivity of the sandcrete brick, T_2 is the thickness of the rendering, and T_{C2} is the thermal conductivity of the cement mortar used for the rendering.

$$U = \frac{0.152}{0.7} + \frac{0.05}{1.122} + \frac{0.05}{1.122}$$

U =0.217 + 0.045 + 0.045
= 0.307 kcal/m^2/h^oC

Likewise the total heat transfer through walling and rendering materials was calculated through Equation 7.

$$Q = U \times A \times \Delta T \times t \quad (7)$$

Where "t" is the time = 2h hrs.
Q = 0.307 x 252 x 20 x 24
Q = **37134.72 Kcal/24h**
But R value adopted was 1.5
Therefore effective Q value = $\frac{37134.72}{1.5}$
= 24756.48Kcal/24h

2.2.2 Heat transfer through the floor

The heat transfer (Q) through the floor of the cold room was calculated through Equation 8.

$$Q = \frac{A \times \Delta T \times t}{R} \quad (8)$$

Where A is the area of the floor = 22 x 9.5 = **209 m^2**
R value adopted = 2.5
t = time (24 hrs.)
ΔT = change in temperature

$$Q = \frac{209 \times 20 \times 24}{2.5}$$

= 40128 kcal/24h

2.2.3 Heat transfer through the concrete decking (roofing) and ceiling

Equation 9 was used to design for the overall heat transfer coefficient of the decking (roofing) and rendering components.

$$U = \frac{T_1}{TC_1} + \frac{T_2}{TC_2} \quad (9)$$

Where:
T_1 is the concrete thickness = 0.152 m,
TC_1 is the concrete thermal conductivity = 1.49 kcal/m/h^oC,
T_2 is the thickness of the rendering = 0.05 m,
TC_2= thermal conductivity of the cement mortar used for the rendering (1.122 kcal/m/h^oC),

$$U = \frac{0.152}{1.49} + \frac{0.05}{1.122}$$

U = 0.102 + 0.045

= 0.147 kcal/m^2/h^{o}C

The heat transfer through the roofing materials (concrete and rendering materials) is calculated through Equation 10.

$$Q = U \times A \times \Delta T \times t \quad (10)$$

Where "t" is the time = 2h hrs.

Q = 0.147 x 209 x 20 x 24

Q = 14747.04Kcal/24h

The heat transfer (Q) through the ceiling (insulating) material was calculated through Equation 11, and R value of 2.5 was adopted.

$$Q = \frac{A \times \Delta T \times t}{R} \quad (11)$$

Where A is the area of the roof = 22 x 9.5 = **209 m^2**

$Q = \frac{209 \times 20 \times 24}{2.5}$

Q = 40128 Kcal/24 h

Therefore, total heats transfer through the roofing and insulation materials =
14747.04 + 40128

Q = 54875.04 Kcal/24h

Therefore total heat transfer through the roofing and ceiling = 31691.52 + 40128 + 54875.04
Q = 126694.56**kcal/24h**

2.2.4 Products load

(a) Cucumber fruits

The product (cucumber) cooling is calculated through Equation 12.

$$\text{Product cooling} = W \times sp \times \Delta T \quad (12)$$

Where: W = cucumber mass, sp = cucumber specific heat, and Δt = temperature difference

Product cooling = 25000 x 0.289 x 20

= 144,500kcal/24h

(b) Paper carton box

Equation 13 was used to calculate the paper carton boxes heat load

$$\text{Paper carton box heat load} = W_B \times sp \times \Delta t \quad (13)$$

Where W_B= mass of the box, and sp = specific heat of boxes

Paper carton box heat load = (625 x 2) x 0.33 x 20

= 8,250 kcal/24h

Total products load = load of the fruits + load of the paper carton box.

Therefore the total products load = 144500 + 8250

= **152,750 kcal/24h**

2.2.5 Respiration load during cold storage

The respiration heat load of the cucumber fruit is calculated through Equation 14.

$$R_H = W \times h_r \quad (14)$$

Where R_H = respiration heat load, W = weight of the cucumber, and h_r is the heat of respiration.

R_H = 25 x 760
= **19,000 kcal/24h**

2.2.6 Internal heat load

Lighting load

The cool room will be lighting with eight (8) 0.2 KW energy saving bulbs. The bulbs will be on for an average of 8 hours per day. The heat load was calculated by using Equation 15.

Q = p x t
15.

Where p is the collect powering rating of the bulbs, and t is the effective time of operation.

Q = (0.2 x 8) x 8
= 12.8 kWh/24h

But 1 KWh/24h = 860 Kcal/24h
Therefore 12.8 kWh/24h = **11008 kcal/24h**

Human load

It was assumed that 5 people will be working inside the cold room at a rate of 6 hours per day. The human load was calculated with the modified formula shown in Equation 16, as described by Evans (2017).

$Q = n \times t \times h$ 16

Where:
n = number of human workers (5),
t = time (6)
h = heat loss per worker (0.5 kW)

Q = 5 x 6 x 0.5
= 15 kWh/24h
= 12900kcal/24h

Air infiltration load

The air infiltration load was calculated through the modified formula shown in Equation 17 (Evans (2017).

$Q = N \times v \times e \times \Delta T$ 17

Where:
N = air changes that occurred inside the storage room due to opening of the cold room doors in a day (8),
v = free volume of the cool room (759.989 m^3),
e = energy per m3 off the incoming fresh air (0.478 kCal/24h), and
ΔT = outside temperature – inside temperature (20^oC)

Q = 8 x 759.989 x 0.478 x 20
= 58096.94kcal/24h

Summation of internal heat load

The total internal heat load was calculated through the summation of lighting load, human load and air infiltration load.

Effective internal heat load (IHL) = 11008.00 + 12900.00 + 58096.94
= 82004.94**kcal/24h**

2.2.7 Total heat load

Total heat load of the cold room is calculated through equation 18.

$$THL = H_s + P_C + R_H + IHL \quad (18)$$

Where:

H_s=summation of heat transfers through the cold room walls and roofing, P_C=cucumber cooling, and IHL=internal heat load.

THL = 126694.56 + 152750 + 19000 + 82004.94

= 380449.50 **kcal/24h**

2.2.8 Design for miscellaneous load

This is loading that occur through human and mechanical activities within the cold room during loading, unloading, products inspection, and others basic operations. To design for the miscellaneous load, 20% of the THL was taken as the miscellaneous load.

Therefore effective heat load = $380449.5 + \left(\frac{20}{100} \times 380449.5\right)$

= 380449.5 + 76089.90

= 456539.40 **kcal/24 h**

2.2.9 Factor of safety

To design for the factor of safety, 5% of the effective heat load was adopted as factor of safety for this cold room.

Therefore the net heat load = $456539.40 + \left(\frac{5}{100} \times 456539.40\right)$

= 456539.40 + 22826.97

= 479366.37kcal/24h

2.3 Refrigeration load calculation

Basic assumption:

The cold room will be powered on 14 hours daily (6 am – 8 pm)

Therefore the refrigeration capacity requirement = $\frac{net\ heat\ load}{time\ of\ operation}$

= $\frac{479366.37}{14}$

Refrigeration capacity **= 34240.46kcal/h**

2.3.1 Design for the refrigeration load

To design for the refrigeration load, we need to convert the kcal values to kJ/h.

From the conversion table 1 kcal/h = 4.1868 kJ/h

Therefore 34240.46 kcal/h = 114494.69 kJ/h

Similarly, the conversion table revealed that one (1) ton of refrigeration = 12660 kJ/h

Therefore 114494.69 kJ/h = $\frac{114494.69}{12660}$

= 9.04tons of refrigeration

Based on this information, the refrigeration unit capacity can be calculated.

1 ton of refrigeration is equivalent to 3.52 kW of cooling.

Therefore, 9.04 tons of refrigeration will require 31.82 kW air conditioning capacity machines.

Remarkably, the cool room will require **6 units of air** conditioning machine each having capacity of 2 tons (7.04 kW) of refrigeration.

3.0 Design of the cold room smart system

3.1 Hardware

These hardware were used for the design of the smart system

Arduino UNO

The cold room was designed with Arduino Uno (ATmega328P model) microprocessor. This microcontroller has a voltage rating ranging from 7 V to 12 V DC, operates at a clock speed of 16 MHz and of 50 mA.

DHT11 sensor

This sensor is designed to regulate the temperature and humidity levels within the storage system. It functions at a current of 2.5 mA and voltage of 5 V DC. Additionally, it is capable of operating within a temperature range of 0°C to 50°C and a relative humidity (RH) range of 20% to 85%.

Relay module

This module performs the function of activating "switch ON and OFF" the air conditioning device. It operates based on instructions received from the microcontroller, allowing for automated control of the cooling unit within the system.

Software Requirements

The smart facility was designed with the C++ programming language, while the instructions were designed by using the Arduino Compiler (IDE). Additionally, the graphical user interface (GUI) of the system, was created using the Blynk Application for Android.

Smart system methodology

The main purpose of this smart system is to control the temperature and relative humidity (RH) levels within the cold room. Data collected by the sensor is processed by the microprocessor and displayed in real-time. This enables the users to have access to accurate and current situation of the cold room interior environmental conditions.

In the design, the sensor provides information to the Arduino UNO for interpretation. Once interpreted, the Arduino UNO refers the interpreted data to the relay module which activates the control hardware, enabling it (the air conditioner) to take necessary actions. The smart system is designed to be powered by a 12-volt DC battery, ensuring its operation even in the absence of external power sources.

The flow chart for the temperature management is presented in Figures 2 and 3. Figure 2 indicates that the cooling unit will be automatically switched “OFF” is the temperature falls below the minimum programmed level (10^{o}C). Similarly, Figure 3 shows that the air conditioner system will be powered “ON” when the inside temperature exceeded the pre-set temperature 14^{o}C. These two flow charts and the programming will help to maintain the internal temperature of the cold room at a range of 10 to 14^{o}C, which is conducive for cucumber fruits storage.

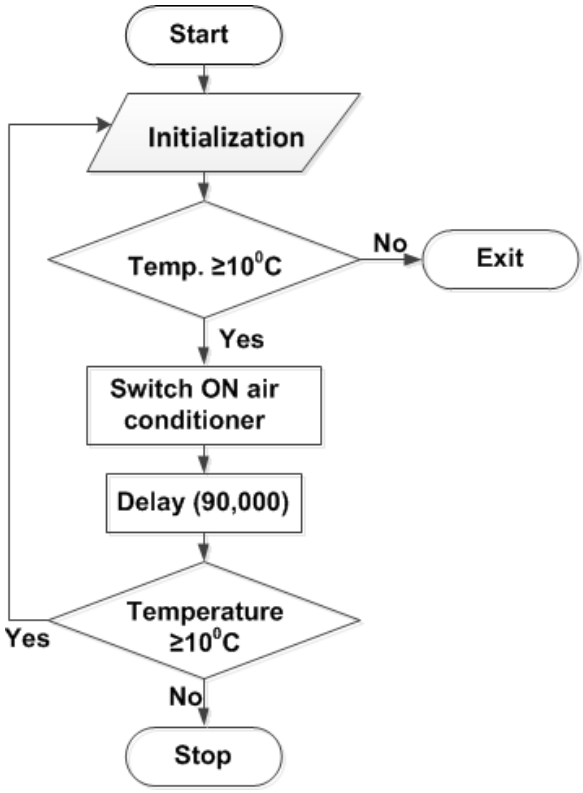


Figure 2: Temperature control (minimum level)

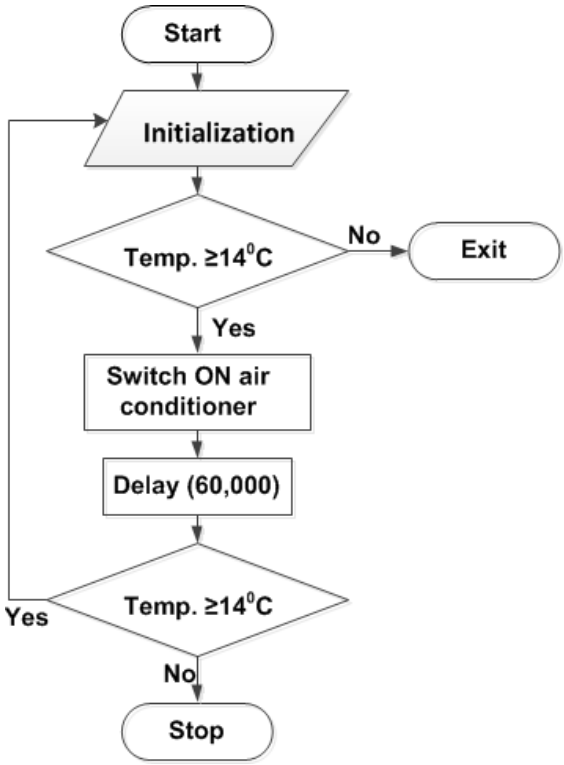


Figure 3: Temperature control (maximum level)

4.0 Conclusion

This research was conducted to design a smart 25 ton capacity of cold room specific for cucumber storage. The calculations revealed that the cold room has the capability to accommodate 25,000 cucumber fruits. To ensure optimal conditions, six air conditioners with a 2-ton capacity each will be utilized to maintain a temperature of 10°C for the stored cucumbers. By effectively controlling the internal; temperature and humidity levels of the cold room, it enhances the preservation of the perishable food item. The development of this designed cold storage room will be useful in the food industry, offering a means of optimizing the quality and quantity of the stored agricultural product.

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